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Device with a heat source formed by a function element that is to be cooled, at least one heat sink, and at least one intermediate layer located between the heat source and the heat sink

#### Background of the Invention

[0001] The invention relates to an array or an apparatus and to a thermally conductive mass for the intermediate layer of such an apparatus.

[0002] "Heat source" according to the invention generally refers to a part of the apparatus or array containing at least one heat generating function element, for example a corresponding component or assembly. In particular, "heat source" according to the invention refers to an electric or electronic component, to a group of several such components, to an integrated circuit or also to an electric or electronic circuit containing one or more such components or circuits.

[0003] "Heat sink" according to the invention refers in general to a part of the apparatus or array according to the invention to which the heat from the heat source is to be transferred in the most optimum manner possible for the purpose of cooling, for example. In particular, "heat sink" according to the invention refers to a part of the apparatus or array according to the invention that serves to cool the electric or electric components or modules.

[0004] "Thermally conductive mass" according to the invention refers in particular to a material in a liquid, semi-liquid/viscous or solid state, which as an intermediate layer between the heat source and the heat sink ensures the optimum transfer of heat to the largest surface area possible, also if the corresponding surfaces provided for the transfer of heat (heat transfer surfaces) between the heat source and

the heat sink are, for production reasons for example, not completely flat and/or are considerably rough.

[0005] Optimum cooling and heat dissipation is essential in electric and electronic components, especially in such components with a high power output or in components containing circuits or modules. Insufficient cooling can result in the destruction of the components and a reduced service life or life time of the corresponding circuit or module. In order to compensate for any uneven and/or rough areas on the adjacent heat transfer surfaces, for example the bottom or cooling surface of a component, an electric or electronic circuit or module and a heat sink (for example a passive or active cooler), normally an intermediate layer consisting of a thermally conductive paste is provided between said heat transfer surfaces. The disadvantage of this method is that after a certain period of operation, many known thermally conductive pastes lose a significant amount of their original thermal conductivity, so that the desired cooling effect of the respective component, circuit or module is lost. This effect is especially pronounced in such applications in which a constant change in the power dissipation and therefore a constant change in temperature occurs during operation, as for example during switching of an electric actuator. In this case, according to an underlying discovery of the invention, the temperature change at the transfer between the heat source (component, circuit or module) and the heat sink apparently causes a mechanical pump effect, with the effect that the thermally conductive paste, and in particular also the components effecting the thermal conductivity of said paste, is concentrated in a reduced surface area, for example in the edge area of the heat transfer surfaces between the heat source and the heat sink, resulting in a severe reduction of

the actual surface available for the transfer of heat and therefore in a reduction of the cooling effect.

[0006] This problem is compounded by the factor of miniaturization and by ensuing increase of the power density particularly of power modules.

[0007] It is an object of the invention to demonstrate an array, arrangement or apparatus that eliminates these disadvantages while enabling the stable transfer of heat between a heat source and a heat sink over an extended period of operation.

#### **Summary of the Invention**

[0008] A thermally conductive paste is disclosed that is suitable particularly also for the intermediate layer of the arrangement according to the invention.

[0009] Through the nanofibers contained in the organic matrix alone, the intermediate layer present between the heat source and the heat sink or the thermally conductive mass of said intermediate layer has a high thermal conductivity. Moreover, the use of nanofibers also makes said intermediate layer stable over an extended period of operation or use, i.e. especially even with frequent changes in temperature in the proximity of the intermediate layer, there is no change, or at least no noticeable change in said layer. According to an discovery of the invention, the nanofibers therefore have a stabilizing effect on the intermediate layer.

#### **Brief Description of the Drawings**

[0010] The invention is described below in detail based on exemplary embodiments with reference to the drawings, wherein:

- [0011] Fig. 1 shows a simplified schematic depiction of the basic structure of an arrangement or apparatus according to the invention;
- [0012] Fig. 2 shows a schematic representation of an apparatus for testing the heat conductivity of the intermediate layer used in the apparatus according to the invention and of the material (thermally conductive paste) used for said layer;
- [0013] Fig. 3 shows a graphic representation of the change in temperature of a sample heated through the intermediate layer according to the invention, together with the temperature gradient for comparison measurements;
- [0014] Fig. 4 - 6 show an enlarged view of the intermediate layer in the apparatus according to Figure 1 between the heat source and the heat sink, for different embodiments of the invention; and
- [0015] Fig. 7 - 11 show various embodiments of an apparatus according to the invention.

#### **Detailed Description of the Invention**

[0016] In Figure 1, a heat source, the thermal energy of which is dissipated through a heat sink 2, is generally designated 1. The heat source 1 is for example an electric or electronic component, preferably an electric or electronic power component, for example a semiconductor component, e.g. transistor, mosfet, diode, or also a laser diode, integrated circuit, thyristor, laser diode and suchlike, or also an electric or electronic circuit (also module), which comprises

one or more electric or electronic components, which generate power loss during operation and therefore must be cooled.

[0017] The heat sink 2 can be of any design whatsoever, so that it is suitable for dissipating the thermal output supplied by the heat source 1. The heat source 1 and heat sink 2 are connected with each other in a suitable manner, so that they are immediately adjacent on two essentially flat surface sides 1.1 and 2.1 (heat transfer surfaces). The heat source 1 and heat sink 2 are for example bolted together or connected and pressed together in another manner.

[0018] In order to maximize use of the entire surface sides 1.1 and 2.1 for optimum thermal transfer despite unavoidable rough or uneven areas, e.g. due to production, i.e. to minimize the thermal transmission resistance, an intermediate ply or layer 3 made from a material with high thermal conductivity is provided between the heat source 1 and the heat sink 2. The intermediate layer 3 or the material forming said intermediate layer is selected so that, at least during operation of the components generating the heat, a thermal transmission connection with low resistance is created between the heat source 1 and the heat sink 2, also in the uneven areas of the thermal transfer surfaces. Furthermore, the thickness of the intermediate layer 3 is as small as possible, for example so that uneven areas of the surface sides 1.1 and 2.1 are leveled out by said intermediate layer 3.

[0019] In the depicted embodiment the thickness of the intermediate layer 3 is between 0.01 and 0.5 mm.

[0020] The material used for the intermediate layer 3 consists in the simplest case of at least one organic component as a matrix and of carbon nanofibers embedded in this organic component, for example single-walled nanotubes,

double-walled or multi-walled nanotubes or in some other form, for example with fishbone surface structures, which enable optimal integration in the organic matrix.

[0021] The nanotubes have a length between 1  $\mu\text{m}$  and 100  $\mu\text{m}$  and a thickness between approximately 1.3 nm and 300 nm, with a ratio of length to thickness of least 10. In a preferred embodiment of the material used for the intermediate layer 3, at least a majority of the nanofibers embedded in the organic matrix have a length greater than 10  $\mu\text{m}$ . The longitudinal orientation of the nanofibers in the intermediate layer is random.

[0022] The percentage of nanofibers in the organic matrix is between 1 and 70 percent by weight in relation to the overall weight of the material or of the thermally conductive mass, wherein with a percentage between 5 and 20 percent by weight results in excellent properties, in particular with respect to thermal conductivity and stability.

[0023] An essential advantage of the intermediate layer 3 is the fact that the use of the nanofibers produces a stable structure for the intermediate layer, i.e. even if the organic matrix at least during operation of the heat source 1 is in a liquid or viscous state, the mass forming the intermediate layer 3 remains stable, i.e. there is no separation or displacement of the nanofibers, for example from the center of the surface sides 1.1 and 2.1 to the edge area, as can be observed with known thermally conductive pastes especially in case of changing temperatures at the heat source. This is obviously due to the fact that the nanofibers are mutually held or fixed in the matrix, in addition to any other additives or components added to the organic matrix.

[0024] Various materials or mixtures of materials, which are already liquid at room temperature or close to room temperature, i.e. at temperatures between 10 and 30°C, are suitable for the organic matrix. A suitable material for the organic matrix in this case is for example oil, such as silicone oil. Materials or mixtures of materials, which are liquid in the temperature range of the heat source 1 during operation, i.e. between approximately 40 and 80°, are also suitable for the organic matrix. A suitable material for the organic matrix in this case is for example thermoplastic synthetic material.

[0025] As indicated in Figure 1 by the arrows P, the heat source 1 and the heat sink 2 are pressed against each other through the intermediate layer 3, with a surface pressure between approximately 0.1 and 100 bar.

[0026] The use of nanofibers made of carbon in the organic matrix features the advantage of higher thermal conductivity for the intermediate layer 3. With a corresponding percentage of nanofibers, for example as high as 10 percent by weight, the material used for the intermediate layer 3 also displays electrically conductive properties, despite a thermal conductivity that corresponds approximately to the thermal conductivity of aluminum.

[0027] Instead of the materials mentioned above, other organic compounds can also be used as matrix components, in particular elastomer organic compounds, such as silicone rubber or also polymers, for example polycarbonate, polypropylene or polyethylene. Especially the use of a matrix made of an elastomer material has the advantage that, due to the elastic design of the intermediate layer 3, changes in the contact pressure P can be compensated at least within certain



limits, so that the intermediate layer 3 is in full contact with both surface sides 1.1 and 2.2 at all times within these limits, thus maintaining the desired large-surface thermal transmission. Such changes in the contact pressure  $P$  can result for example from changes in the temperature of the heat source 1 and from ensuing changes in length of the elements mutually tensioning against the heat source and the heat sink.

[0028] With the test array depicted in Figure 2, the thermal conductivity of the intermediate layer 3, consisting of a matrix made of silicone oil with a percentage of nanofibers of 10 percent by weight, was tested in relation to the overall mass. The test array generally designated 4 in this drawing consists essentially of two square metal plates 5.1 and 5.2 made of aluminum. Each of the two plates has an edge length of 5 cm and a thickness of 0.2 m and the plates are parallel and at a distance from each other, with a gap 6 of 150  $\mu\text{m}$ . On the surface side of the plate 5.1 facing away from the plate 5.2 there is an electric heating device 5.3, with a power output of 1.2 watts. The plate 5.2 is blackened on its surface side facing away from the plate 5.1 so that the temperature of the plate 5.2 can be measured by contactless measuring by means of an infrared camera 7.

[0029] Figure 3 depicts the temporal gradient of the temperature measured with the infrared camera 7, with curve a providing that there is an air gap 6 of 150  $\mu\text{m}$  between the two plates 5.1 and 5.2, with curve b providing that the gap 6 is filled with pure aluminum, and with curve c providing that the gap 6 is bridged by the material of the intermediate layer 3, i.e. by a paste consisting of the organic matrix of silicone oil with a percentage of carbon nanofibers of 10 percent by weight.

[0030] As shown in Figure 3, curve c very nearly approximates curve b and also progresses clearly above curve a, which confirms the advantageous high thermal coefficients of the mass consisting of the organic matrix and the nanofibers.

[0031] Through a suitable treatment of the nanofibers, namely through a graphitizing step at a temperature between approximately 2700 and 3100 °C, the thermal conductivity of the nanofibers and therefore the thermal conductivity of the mass containing said nanofibers can be further improved.

[0032] It was assumed above that the mass forming the intermediate layer 3 consists only of the organic matrix and the added nanofibers. Further components or additives are conceivable, for example thermally conductive ceramics in powder form, for example  $\text{Al}_2\text{O}_3$ , AlN, BN,  $\text{Si}_3\text{N}_4$ , SiC, BeO, ZrO. Instead of these or in addition to these, further additions or components are possible, for example in the form of metal particles, e.g. of silver, copper, gold or of alloys of these metals. In particular, metal particles or particles made of metal alloys can be used as additives, which (particles) change into molten state at temperatures above 50 °C.

[0033] In a further possible embodiment the nanofibers contained in the organic matrix are coated at least partially with at least one metal or one metal alloy, for example electrically or electrolytically and/or chemically coated.

[0034] Figure 4 shows again in an enlarged partial representation the intermediate layer 3 consisting of the organic matrix and the nanofibers 8 embedded in this matrix, in addition to any other additives or components. The nanofibers designated 8 in Figure 4 are depicted so that they are embedded in the matrix in tangled or crumpled form.

[0035] Figure 5 shows in a depiction similar to Figure 4 the intermediate layer 3 in a further possible embodiment, wherein the nanofibers 8 at least for the most part are oriented longitudinally so that they are perpendicular or approximately perpendicular to the surface sides 1.1 and 2.1. This is achieved for example by the fact that an electric voltage, for example the voltage of a DC source 9, is applied to the surface sides 1.1 and 2.1 made of electrically conductive material and functioning as electrodes. The voltage is selected so as to produce an electric field intensity of approximately 1 volt per  $\mu\text{m}$  within the intermediate layer 3. Due to the orientation of the nanofibers 8, the thermal conductivity of the intermediate layer 3 is improved significantly. Furthermore, the voltage also results in additional stabilization. In a practical embodiment, this low electrical field intensity within the intermediate layer 3 can easily be achieved, for example, by a corresponding difference in potential between the heat source 1 and the heat sink 2.

[0036] Figure 6 shows as a further possible embodiment in a depiction similar to Figure 4 the intermediate layer 3, in which the nanofibers 8 are oriented longitudinally so that they are parallel to the surface sides 1.1 and 2.1.

[0037] In deviation from Figures 4 - 6, the nanofibers embedded in the organic matrix can be at least for the most part connected with each other to form a two- or three-dimensional structure, for example in a kind of web or a non-woven material (fleece) or a three-dimensional porous structure or a three-dimensional network or screen.

[0038] The following Figures 7 - 10 show various possible embodiments for the heat sink 2. Figure 7, for example, shows again in a schematic depiction an apparatus according to the

invention with the heat source 1 and a heat sink 2a, which is formed by a cooling element or passive cooler 10 with a plurality of cooling fins or pins or pin-like projections on the side facing away from the heat source 1. The cooler 10 is located in the air stream of a blower or fan 11 for the purpose of dissipating the heat.

[0039] Figure 8 shows the apparatus according to the invention with a heat sink formed by an active cooler 12. The active cooler 12 is for example a micro-cooler, as described for example in DE 197 10 783 A1. A coolant, for example water or a coolant containing water, circulates through said cooler 12, which for this purpose is located within a cooling circuit, comprising a circulating pump 12, an external re cooler 14 with a blower 15 and a compensating or collection tank 16 for the coolant.

[0040] Figure 9 shows an embodiment of the apparatus according to the invention in which the heat sink is formed by a heat pipe 17. Said heat pipe 17 contains in its elongated, hermetically sealed housing a coolant that is vaporizable through heating, for example alcohol or some other vaporizable organic medium. Also within the elongated, sealed housing there are at least two parallel flow paths, which are connected with each other at least at the two ends of the housing, namely one channel-like flow path for the vaporized medium and one capillary-like flow path for the liquid phase of the coolant. The heat source 1 is connected via the intermediate layer 3 to one end of the heat pipe 17. On the other end of the heat pipe 17 there is a cooler 18, comprising for example a plurality of cooling fins or corresponding projections or pins, which (cooler) is located within the air stream of a blower 19.

[0041] Figure 10 shows as a further possible embodiment an apparatus according to the invention in which the heat sink 2 is formed by one heat pipe 20 serving as a heat spreader and one cooler 21 corresponding to the cooler 10. The cooler 21 is likewise located within the air stream of a blower not depicted or the cooler 21 is designed corresponding to the cooler 12 as an active cooler through which a coolant circulates, for example as a micro-cooler. The heat pipe 20 corresponds in its function to the heat pipe 17, however with the difference that the area where the heat source 1 is provided is located in the center of the housing of the heat pipe 20, so that the latter is symmetrical at least in relation to a plane oriented perpendicularly to the surface side 1.1 of the heat source 1.

[0042] One intermediate layer or intermediate ply corresponding to the intermediate layer 3 is provided both between the heat source 1 and the top of the heat pipe 20 and between the bottom of this heat pipe and the adjacent surface of the cooler 21. Furthermore, in all embodiments depicted in Figures 7 - 10, the components located on both sides of the respective intermediate layer 3 are pressed together in the manner described above, namely with a surface pressure between 0.1 and 100 bar.

[0043] Figure 11 shows an embodiment in which an electronic circuit 23 is provided using a ceramic-metal substrate, preferably a copper-ceramic substrate, on the heat sink again generally designated 2 in this drawing. Said electrical circuit is at least one electrical or electronic power component 24, for example a diode, a semiconductor switching or control element, such as a transistor (or also a mosfet), thyristor, etc. or a laser diode. The substrate 22 consists in the known manner of a ceramic layer, for example an aluminum

oxide or aluminum nitride ceramic, and is provided by means of the likewise known DCB or active soldering process on both sides with a metallization formed by a metal foil, for example copper foil. The upper metallization 2.2 is structured to form strip conductors, contact surfaces, etc. The power component 24 is also affixed to this metallization, for example by means of soldering. The lower metallization 22.3 is used for heat spreading and cooling and is connected via the intermediate layer 3 with the heat sink 2, which likewise can be designed in any manner corresponding to the respective application, for example as described above in connection with Figures 7 - 10.

[0044] The invention was described above based on exemplary embodiments. It goes without saying that numerous modifications and variations are possible without abandoning the underlying inventive idea on which the invention is based.

## Reference marks

1	heat source
1.1	heat transfer surface or surface side of the heat source
2	heat sink
2.1	heat transfer surface or surface side of the heat sink
3	intermediate ply or layer
4	measuring or testing set-up
5.1, 5.2	aluminum plate
5.3	electric heating device on plate 5.1
6	clearance
7	infrared camera for contactless temperature measuring
8	nanofiber
9	voltage source
10	passive cooling element
11	blower
12	active cooler
13	circulating pump
14	recooler
15	blower
16	compensating tank
17	heat pipe
18	cooling element
19	blower
20	heat pipe as heat spreader
21	cooler
22	metal-ceramic substrate
22.1	ceramic layer
22.2, 22.3	metallization

- 23 electric or electronic circuit
- 24 electric or electronic power component
- a, b, c temporal temperature gradient